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INTRODUCTION

The Institute for Computer Applications in Science and Engineering (ICASE) is operated at the Langley Research Center (LaRC) of NASA by the Universities Space Research Association (USRA) under a contract with the Center. USRA is a nonprofit consortium of major U. S. colleges and universities.

The Institute conducts unclassified basic research in applied mathematics, numerical analysis, and computer science in order to extend and improve problem-solving capabilities in science and engineering, particularly in aeronautics and space.

ICASE has a small permanent staff. Research is conducted primarily by visiting scientists from universities and from industry, who have resident appointments for limited periods of time, and by consultants. Members of NASA's research staff also may be residents at ICASE for limited periods.

The major categories of the current ICASE research program are:

a. Numerical methods, with particular emphasis on the development and analysis of basic numerical algorithms;

b. Control and parameter identification problems, with emphasis on effective numerical methods;

c. Computational problems in engineering and the physical sciences, particularly fluid dynamics, acoustics, and structural analysis;

d. Computer systems and software, especially vector and parallel computers.

ICASE reports are considered to be primarily preprints of manuscripts that have been submitted to appropriate research journals or that are to appear in conference proceedings. A list of these reports for the period April 1, 1986, through September 30, 1986, is given in the Reports and Abstracts section which follows a brief description of the research in progress.

Presently, ICASE is operated at NASA Langley Research Center, Hampton, VA, under the National Aeronautics and Space Administration, NASA Contract No. NAS1-18107. In the past, support has been provided by NASA Contracts No. NAS1-17070, NAS1-17130, NAS1-15810, NAS1-16394, NAS1-14101, and NAS1-14472.

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RESEARCH IN PROGRESS

Saul Abarbanel

Work continued in collaboration with A. Bayliss and L. Lustman on the problem of non-reflecting boundary conditions for the compressible Navier-Stokes equations. We were able to show that under the constant total enthalpy assumption, long wave perturbations do not decay for $M_\infty > 1.9$. The corrected formulation (accounting for the energy equation) gives decaying modes for all speeds and wall temperature. The time-consistent formulation has been modified to allow for algorithms with local time stepping. The theory being developed can possibly explain the acceleration to steady state observed by using a local time step. Numerical experiments are being initiated now.

Research on operator splitting for hyperbolic PDE's was carried on with D. Gottlieb and P. Dutt. It was shown theoretically that if splitting leads to one of the operators being in Jordan form, polynomial growth results. Implications for current algorithms are being examined now.

Loyce M. Adams

Collaborative work with Randall LeVeque and David Young has led to the determination of the optimal relaxation parameter for the SOR method applied to the 9-point Laplacian. We considered several orderings of the equations, including the natural rowwise and multicolor orderings, all of which lead to nonconsistently ordered matrices, and found two equivalence classes of orderings with different convergence behavior and relaxation parameters.

These results were obtained by using Fourier analysis applied to the error equations for the SOR method. Garabedian, in 1956, viewed the SOR method for the 9-point Laplacian as a discretization of a time dependent partial differential equation and gave a relaxation parameter based on an analysis of the PDE. Our results differ with Garabedian's and we explained why both results are, in a sense, correct.

It has been suggested in the literature to modify the SOR method for the 9-point Laplacian by using a Red/Black ordering with old information for nodes of the same color from the center point of the stencil. By doing so, the method would parallelize by using only two colors. We examined this method via the same Fourier analysis techniques and showed that the convergence rate to be more like Gauss-Siedel than true SOR.

H. T. Banks and K. Ito

We have continued our efforts on development of a hybrid scheme for computation of feedback control gains in large but finite dimensional system LQR problems. Our method, based on Chandrasekhar, Newton-Kleinman, and variable acceleration parameter Smith method components, has proved to be very effective computationally. In comparisons with the Potter method, it has given significant improvements on examples such as boundary flux control of parabolic equations which have been approximated by large order finite element (linear splines) systems. On the examples studied to date, we have demonstrated that the method is $O(N)$ (vs. $O(N^3)$ for the Potter method) where N is the dimension of the approximating system.

H. T. Banks and Fumio Kojima

We are studying state estimation problems for the stochastic vibration system of flexible beams with tip bodies. The system dynamics is described by a stochastic hyperbolic partial differential equation with the boundary conditions which include a stochastic differential equation. Some results have been obtained for mathematical formulations. From now on, this work will be directed at the computational procedures for implementing the state estimation problem considered here.

Additional research was begun directed at solving the problem of domain identification for a thermal diffusivity measurement system of composite materials. This problem is concerned with the identification of structural flaws in aerospace systems which may not be detectable by visual inspection.

H. T. Banks and Georg Propst

Together with R. J. Silcox (Acoustics Division, LaRC) boundary conditions for the active noise suppression problem in the one-dimensional time domain have been formulated. For several possible choices of the state space the semigroups generated by the corresponding Cauchy problem are investigated. To treat the problem as a regulator problem, the most feasible formulation with regard to numerical approximations has to be determined. In case of a wave duct with parameterized sources, the analytic solution to the wave equation with semireflecting boundaries is used to investigate optimal locations, amplitudes, and frequencies of the inputs.

H. T. Banks and I. G. Rosen

We have developed computational methods for the estimation of functional material parameters in distributed parameter models for flexible structures. More specifically, we have developed spline-based finite element methods for the identification of spatially varying flexural stiffness and Voigt-Kelvin viscoelastic damping coefficients in Euler-Bernoulli models for the transverse vibration of flexible beams with tip appendages. Our effort has yielded a convergence theory and included extensive numerical studies.

Also, we have been able to demonstrate the feasibility and effectiveness of our schemes using actual laboratory data taken from an experimental structure. The data were obtained from an experiment run on the RPL structure at the C. S. Draper Laboratories. This structure consists (in part) of a cantilevered beam with a gas-jet thruster at the free end. Using measurements of acceleration at the tip, we were able to identify unknown parameters in a distributed parameter based model for the dynamics of the structure.

Alvin Bayliss

Work continued in collaboration with L. Maestrello (Transonic Aerodynamics Division, LaRC), P. Parikh (Vigyan Research Associates, Inc.), and E. Turkel

on the computation and active control of unstable, spatially varying waves in a boundary layer. A three-dimensional program for spatially unstable waves using fourth order finite differences has been developed and tested for low Reynolds number flows. Computations at higher Reynolds number are being conducted.

In addition, a study was initiated (with L. Maestrello and P. Parikh) to compute the acoustic radiation generated by two dimensional, spatially growing wave packets in a boundary layer over a surface with concave-convex curvature. The acoustic field is calculated by computing a near field solution of the Navier-Stokes equations and using this solution as input to a program which solves the convective wave equation. The resulting acoustic field illustrates a super directivity (beaming in a preferred direction) for some choice of parameters. An ICASE report is being prepared on this work.

Dennis W. Brewer

Research is continuing on parameter estimation problems associated with linear evolution equations in infinite-dimensional spaces. A general algorithm based on quasi-linearization has been established along with its local convergence properties. The algorithm has been numerically tested on linear delay-differential equations. Numerical experiments indicate that the method converges rapidly when used to identify two unknown delays together with two or three unknown coefficients using simulated data. Future research will involve continuing numerical experimentation and improvements in the theory to accommodate a wider class of problems.

Dennis W. Brewer and J. Steven Gibson

We are continuing our efforts to develop robust software routines for identifying parameters in robotic manipulators. The programs use numerical integration of nonlinear differential equation models and nonlinear optimization algorithms. This work is in conjunction with J. Pennington and

F. Harrison (Information Systems Division, LaRC) who have provided experimental data. Our previous research indicates a need to model the integrated electro-mechanical system to reduce parameter sensitivity. We have obtained data and have tested models which include coupled physical and actuator dynamics. Good fits to experimental data have been obtained using these methods. In addition, input optimization should be a fruitful area for future research.

John Burns

The development of fast computational algorithms for control of various aerospace systems is the central theme of a number of research issues currently being studied with G. Propst, K. Ito, and R. Fabiano (Brown University). The convergence of suboptimal feedback gain operators to optimal feedback gain operators is assured only if the numerical scheme is stable and consistent with the system and its adjoint. If the dynamical system is not self-adjoint, then computational algorithms for optimal control design must be developed that approximate both the system operators and their adjoints. Such problems occur in fluid flow control problems, active flutter suppression, and in the design of optimal controllers for flexible structures when viscoelastic and thermodynamic damping effects are important. Work is under way to develop computational algorithms for control of such systems that are fast enough to be practical design tools and robust enough to capture the important system properties of the distributed parameter system.

Pravir Dutt

Work is continuing with David Gottlieb and Saul Abarbanel on splitting methods for low Mach number Euler flows. We write the Euler equations as a symmetric hyperbolic system of equations so that the coefficient matrices of the differential operators are functions of the sound speed and fluid velocities only. This permits us to propose an optimal splitting technique for low Mach number Euler flows. In addition, we investigate some currently used non-symmetric splitting techniques and point our their deficiencies.

Robert E. Fennell

The overall objective of this research is the development of analytical and numerical methods in a unified mathematical setting for the modeling, analysis, and control of multivariable systems. System structure, time delays (transport, communication, digital control, human operator), nonlinearities, and randomness will be taken into consideration.

Developments in the control of flexible aircraft with multiple control surfaces, thrust vectoring, digital control implementation, and multiple objectives motivate this research. Attention will focus upon the problem of robust control system design for time delay systems. The problem of an uncertain plant stems from a basic modelling dilemma. The more detail one includes in a model the more difficult one makes the parameter estimation problem. Difficulties can be compounded by choosing an inappropriate representation of the plant model, for instance a model which is not robust. Since feedback control laws must be developed in terms of the plant representation, there is a temptation to ignore these difficulties and insist on models of a particularly simple form. Computational experience suggests that input/output models determined by observing the response of the system to specified inputs are insensitive to measurement errors. Consequently control laws based upon such models should also be insensitive to uncertain parameters. These ideas are being pursued in the analysis of feedback stabilization problems for uncertain plants.

Related topics under consideration include the digital approximation and simulation of feedback control problems for hereditary systems, the delination of canonical forms and related control design strategies for the decentralized control of large scale systems, and the development of control design methods for a class of nonlinear hereditary systems.

George J. Fix

Analysis of mixed finite element and finite volume schemes for structural mechanics continues. Special attention is given to composite materials and polymers.

There is also work on iterative methods for large algebraic systems. Attention is given to relaxation methods with spatially varying relaxation parameters. Emphasis is given to algorithms which can exploit parallel computer architectures.

James Geer

The development and study of a hybrid perturbation/Galerkin method to determine how the method might be applied to some fluid dynamic and scattering problems is underway. The method is based on some of the concepts and formalisms of the reduced basis method, which is a semi-numerical, semi-analytical method that has been used to solve a variety of nonlinear boundary value problems in solid mechanics. Several model problems are being studied to help better understand the method and to determine for what types of problems the method is applicable. At present, these model problems include some two-point boundary value problems with boundary layers and some simple exterior fluid flow and scattering problems involving a slender body. Work on the method itself is being done with Dr. Carl Andersen (College of William and Mary), while possible applications are being discussed with Dr. Eddie Liu (Low-Speed Aerodynamics Division, LaRC).

Another study involves the use of the symbolic computation system MACSYMA and perturbation methods to investigate some free and forced nonlinear oscillations. The method of multiple time scales has been implemented using MACSYMA and applied to the problem of determining the transient responses of the van der Pol and Duffing oscillators when the applied force consists of a sum of periodic terms with different frequencies. The conditions under which the system will experience frequency entrainment are being investigated. This work is being done with Dr. Carl Andersen (College of William and Mary).

Research is underway to determine the possibility of using some of the ideas of uniform slender body theory for the problem of subsonic flow past a fully three dimensional wing with sharp trailing edges and wing tips. A preliminary study will attempt to include trailing (wing-tip) vorticity effects on a three-dimensional thin wing with arbitrary planform. This work is being

done with Dr. Eddie Liu (Low-Speed Aerodynamics Division, LaRC) and Prof. Lu Ting (New York University).

Investigations are underway concerning some fundamental properties (both from theoretical and computational points of view) of a class of "almost" singular integral equations of the first kind which are useful in representing the solution to certain elliptic exterior boundary value problems. These equations typically have the property that the domain of integration R is a proper subset of the domain of validity D of the equation. Special consideration is being given to the idea of analytically continuing the solution into the domain D. Applications of the results will be useful in several two and three dimensional problems involving slender or thin bodies. The symbolic manipulation system MACSYMA has been used in some of the preliminary investigations.

J. S. Gibson and I. G. Rosen

We have been developing an approximation theory for the optimal discrete-time linear-quadratic-Gaussian (LQP) problem for infinite dimensional systems. In particular, we have been looking at systems involving unbounded input and/or output operators. This class of problems includes control and estimation problems for distributed parameter systems describing the vibration of flexible structures with boundary control and strain or acceleration measurements. Our study has yielded a convergence theory for feedback control laws, estimator gains, and compensators. An extensive numerical study is currently underway.

Also, we are continuing our efforts to develop computational methods for the identification of material parameters in distributed parameter models for flexible structures using modal or spectral data---that is, natural frequencies and mode shapes.

David Gottlieb

We have developed upwind spectral schemes for discontinuous hyperbolic equations. The method yields high accuracy far away from the shock and is essentially nonoscillatory. In this stage, the method is limited to the Fourier-Galerkin method. Work is in progress in extending this result.

We investigated (with P. Dutt and S. Abarbanel) splitting methods for the Navier-Stokes equations. The main result is that splitting should be symmetric. We suggest a new formulation of the Navier-Stokes equations in order to get a symmetric system of equations.

Together with D. Funaro (Brown University and Pavia University), we study preconditioners for first derivative spectral matrices in two dimensions.

Stability theory for spectral methods for hyperbolic systems is being developed and applied to multidomain techniques.

Chester E. Grosch

A three-dimensional, time dependent Navier-Stokes code in vorticity and velocity variables has been developed in collaboration with T. Gatski (High-Speed Aerodynamics Division, LaRC) and M. E. Rose. This code is being used to study three-dimensional vortex dynamics; in particular the phenomena of vortex breakdown is being simulated by R. Spall (Old Dominion University) and T. Gatski. The results of these calculations have suggested that vortex breakdown can be correlated by a Rossby number criterion. Examination of all data, experimental as well as computational, known to us (Spall, Gatski, and Grosch) show that this is the case.

Calculations of the stability of a family of vortex flows are being carried out with M. Korani (Old Dominion University). These vortex flows are exact solutions of the Navier-Stokes equations. It is hoped that the results of these calculations will illuminate the dependence of the stability (or lack of it) on such parameters as Reynolds number and pressure gradient.

The study, in collaboration with R. Fatoohi, of parallel algorithms for elliptic problems is continuing. A series of tests on the MPP at NASA Goddard have been completed. Both problems which fit on the array as well as oversize

problems have been used for the tests. Similarly, a modification of this relaxation algorithm has been used on FLEX/32 and performance measured as a function of problem size. Finally, the algorithm has been adapted to run on the CRAY-2 and a series of performance tests carried out. All of these results are now being written up.

Ami Harten

We continue the design and the analysis of high-order accurate essentially non-oscillatory (ENO) schemes for shock calculations. These schemes share many desirable properties with the older total-variation-diminishing (TVD) schemes, but they can be made accurate to any finite order, including at extrema of the solution.

In designing these schemes, we have adopted Godunov's point of view, in which the conservation form is an approximation to the cell-averages of the solution. To implement Godunov's approach, we need to tackle two major tasks: (i) To find a technique to reconstruct a piecewise smooth function from its given cell-average, without introducing large spurious oscillations at discontinuities. For this purpose, we have introduced a new interpolation technique that when applied to piecewise smooth data gives high order accuracy wherever the solution is smooth, but avoids having a Gibbs phenomenon at discontinuities. (ii) To find a relatively simple approximation to the solution-in-the-small of the piecewise polynomial initial value problem (i.e., Generalized Riemann Problem). For this purpose, we analyze the data corresponding to piecewise smooth entropy solutions and show that the solution-in-the-small can be adequately approximated by local linearization techniques.

Future research will concentrate on applications to practical problems and various extensions.

Yousuff Hussaini

We continue to investigate the prototype problems of stability and transition in Poiseuille flow, Blasius flow, and Taylor-Couette flow. Some detailed results on the fundamental type instability of the center modes in Poiseuille flow and the effect of wall heating on the secondary instability in Blasius flow are presented in ICASE Report No. 86-57. Nonlinear interactions among different types of waves are under consideration. Preliminary results on the existence of a certain type of secondary instability in a supersonic compressible boundary layer are reported in ICASE Report No. 86-39. Research is now focused on the influence of compressibility on the instability mechanisms observed in low Mach number flows. In the case of the Taylor-Couette flow, some representative results pertaining to two-cell/one-cell exchange process, and their comparison with experiments, are presented in ICASE Report No. 86-59. Work is continuing on the three-dimensional flow in finite cylinders of small aspect ratio. The purpose is to simulate the route to chaos as observed in some experiments and establish the relation between Navier-Stokes solutions and chaos theories based on model equations.

Our combustion research concerns supersonic reacting flows relevant to scramjet engines. In these flows, the usual assumptions of near equilibrium and fast chemistry may not hold. Keeping the chemistry simple, attempts are underway to study the ignition, flame holding, and flame propagation phenomena (including flame front/shock interaction and flame front/turbulence interaction). The theoretical approach consists of multiple scale asymptotics and full scale numerics. Asymptotic methods play a unique role by providing well founded results in suitable limiting cases. They can be used to verify and be verified by numerical solutions which provide results in the range of conditions of interest not amenable to asymptotic treatment.

This program of research is being carried out in collaboration with J. P. Drummond (High-Speed Aerodynamics Division, LaRC), G. Erlebacher (High-Speed Aerodynamics Division, LaRC), C. L. Streett (Transonic Aerodynamics Division, LaRC), and T. A. Zang (High-Speed Aerodynamics Division, LaRC).

K. Ito and R. Powers

Optimal control problems that have unbounded input and output operators occur frequently in applications. Numerical methods for solving such problems often involve large systems which are computationally expensive. For a large class of problems involving bounded input and output operators, it has been shown that computacional reductions may be achieved through solving what are known as the Chandrasekhar equations. We have derived an infinite dimensional version of these equations for a large class of unbounded input and output operators. Methods for numerically solving these optimal control problems via the Chandrasekhar equations are currently under study.

Tom L. Jackson

One of the most outstanding problems in combustion theory is the Deflagration-to-Detonation Transition (DDT) phenomenon. Experimentally, as a turbulent deflagration wave accelerates in a gas tube, it creates a shock wave ahead of it. Somewhere between the flame and shock wave a "hot spot" develops, eventually leading to a reacting blast wave. If the strength is sufficiently large, the blast wave overtakes the shock, leading to the formulation of a detonation wave. We continue our investigation into the birth process of hot spots in reacting gases. Recently, the initial stages of such a birth have been studied for interior and boundary hot spots. We are currently investigating techniques to develop the solution further in time, describing the complete history to formation of blast waves. This work is being done in collaboration with A. Kapila.

A current research effort at LaRC is focused the understanding of important phenomena connected with supersonic reacting mixing layers. We develop a mathematical model that examines, qualitatively, the combustion process that occurs when two gases mix at supersonic speeds at the trailing edge. We are developing models to examine the ignition process that takes place in this region. This work is being done in collaboration with M. Y. Hussaini.

Harry Jordan

Implementation of the Force programming system on the FLEX/32 computer has led to a better understanding of some of the constructs included in this parallel processing extension to Fortran. The production of a common version of the Force running on both the Encore Multimax and on the FLEX/32 computers led to a regularization of the parallel name scope properties of variables. The parallel property of a variable name being private to one process or shared by all processes is strictly orthogonal to any name scope property of the underlying Fortran language. This is an important realization in light of the fact that several manufacturers have tied the parallelism scope of a variable to some language scope rule in their parallel extensions to sequential languages.

Identical versions of the Force are now running on both the FLEX/32 and the Multimax, and a new manual has been produced defining the system. Timing tests on the FLEX/32 show good speedup and effective use of up to 18 processes on dense Gaussian elimination with partial pivoting on a 300 by 300 matrix.

David Kamowitz

Multigrid algorithms have proven themselves to be powerful tools for the numerical solution of certain partial differential equations. However, numerous questions remain. In particular, what is the best selection of components and parameters for a given problem? In addition, when implementing multigrid algorithms on a parallel machine a number of issues need to be resolved, such as what measures are necessary to balance the computational work among the various processors during each multigrid cycle?

To address these issues, we are undertaking a number of investigations. The first investigation consists of analyzing a particular multigrid algorithm for the solution of singularly perturbed boundary value problems. In this study, we show that the rate of convergence for the multigrid algorithm does not suffer due to the effects of the singular perturbation. Another investigation, conducted with Shlomo Ta´asan, consists of implementing a multigrid algorithm for the solution of the steady state elasticity equations on the Flex/32 multicomputer.

Steve Keeling

There are two areas of activity. First, some parameter estimation projects are coming into sharper focus through interaction with the Nondestructive Evaluation group at LaRC. Also, work is continuing on Galerkin/Runge-Kutta methods for evolution equations.

Implicit Runge-Kutta methods have very attractive properties with regard to stability and implementation. However, we are discovering some alarming consistency characteristics. Specifically, if an IRKM with "classical" order $v > 1$ is used to solve a test problem, for which order v is observed, it can happen that only order 1 is achieved for a more serious problem, even if the solution is infinitely smooth. The proofs show that in addition to being smooth, the solution should be in the domain of powers of the elliptic operator, as for example, solutions of the heat equation are. Nevertheless, while there is interest in sharpening theorems which predict convergence rates, I have found a way of implementing IRKM's so that high order convergence can be proved without restrictive conditions on the solution. I am now assembling computational evidence to support these results.

David Kopriva

Research continued on spectral methods applied to the equations of compressible gas-dynamics. A study of the smoothing of Fourier approximations to discontinuous problems was completed in which a comparison was made between physical and Fourier space filtering. High order and spectral accuracy can be obtained for a scalar linear problem by filtering. A multidomain spectral method has been applied to the solution of several simple fitted-shock/turbulence interaction problems. The multidomain discretization removes the need for large numbers of points or for filtering. A study of amplification of homogeneous isotropic turbulence will be made next.

Randall J. LeVeque

A variety of high resolution methods has been developed recently for solving systems of conservation laws (such as the Euler equations) in one space dimension. Although these can be generalized to more than one dimension by dimensional splitting, it is preferable to derive more fully multidimensional algorithms based on the high resolution principles. One possibility currently being studied is a finite volume method in which one dimensional Riemann problems solved at cell interfaces are used to define two dimensional waves propagating over the grid. By linearizing wave interactions, such an approach can be used on arbitrary unstructured grids. One application of particular interest is a Cartesian grid cut by an irregular boundary.

Chris C. H. Ma

Results have been obtained regarding the robustness of discrete time adaptive control systems. It has been shown that provided the persistency of the excitation condition is satisfied by the regressor vector, a class of multi-input multi-output discrete time adaptive control systems is robustly globally stable against not only nonzero unmodeled dynamics but also bounded internal as well as external noises. These results should enhance the practitioner's confidence in applying adaptive methodologies in practical control problems.

Research will be continuing perhaps in the area of applying adaptive control to active acoustic noise cancellation problems.

Nessan Mac Giolla Mhuiris

Work on vortex breakdown and vortex flow simulation is continuing. New methods for the solution of the Navier-Stokes equations governing the flow of viscous, incompressible fluids are being developed.

Nessan Mac Giolla Mhuiris and Pravir Dutt

Work is in progress to analyze the spatial and temporal behavior of turbulent flow fields. One aspect of our work is diagnostic in nature viz. to design efficient and reliable codes which can calculate the Liapaunov exponents, information dimension, etc. of a turbulent data set. Another aspect would be to study via both computer simulation and analysis of the relation between Eulerian and Lagrangian chaos for simplified models of dynamical systems which incorporate some features of the Navier-Stokes equations.

Piyush Mehrotra

BLAZE is a recently designed scientific programming language employing functional procedure calls. The BLAZE program transformation system maps BLAZE source programs to multiprocessor architectures. Recent work has focused on mapping BLAZE to the IBM Research Parallel Processor, to the Flex Multiprocessor at LaRC and Purdue, and to the Butterfly at the University of Utah.

As a convenient way to study program transformations for such architectures, we have designed an explicit-tasking language, Extended-BLAZE, built on top of BLAZE. Performance analysis of E-BLAZE tasking and communication constructs, and study of complex program transformation, such as automatic domain decomposition, is currently underway.

In a related effort, we are looking at the possibility of providing object-oriented features within BLAZE. These should make it possible to allow "state" and abstractions in a functional language in a relatively clean way. Such features are necessary in order to accommodate large data structures, such as files and data bases, and may also provide an elegant interface to programs in other languages, such as FORTRAN.

Aside from the work on BLAZE, we have also been studying problems in network design. A new class of networks, called synchronized packet interconnections networks, or SPINs, has been developed. These networks can provide very high performance, and also provide the unique capability of being able to

support architectural heterogeneity. That is, different architectural modules requiring differing communication channel bandwidths can be interconnected with the same large network.

One interesting possibility here would be to construct heterogeneous embedded systems such as those required for the NASA space station. Such networks can also be used in high performance cluster architectures, such as the Cedar architecture. The possibility of programming such systems via Object-BLAZE is currently being explored.

Vijay K. Naik

In the past two years, as typed variety general purpose MIMD architectures has appeared as commercial products. Many algorithms suitable for parallel processing have been proposed. The development, on parallel machines, of application codes for solving problems of practical importance has also been reported. In spite of these, several difficulties exist in implementing nontrivial problems efficiently on the multiprocessor systems. These difficulties are primarily because of the lack of methodologies and tools that can automate the process of matching the rates and the amounts of data that must be transferred among the various computational tasks, with the structure and the capacity of the underlying interconnection network.

The study undertaken here is aimed at developing methodologies that will characterize MIMD architectures and will quantify the architecture and algorithm dependent parameters which contribute to the communication delays. Various existing as well as proposed architectures and important algorithms are currently under investigation. It is hoped that the outcome of this research will help towards automating the process of efficient parallel implementations.

Vijay K. Naik and Shlomo Ta'asan

Algorithms based on multigrid techniques are known to be among the most efficient methods for solving partial differential equations. On sequential machines, a wide class of problems discretized on a grid with n points requires only $O(n)$ arithmetic operations to obtain a solution to within the truncation error of the discretization. This makes the multigrid methods optimal on the sequential machines. In addition to this optimal property, many aspects of the multigrid algorithms are highly parallelizable making these methods attractive for implementation on multi-processor systems. Several researchers have studied the effects of parallelizing the intra-grid and inter-grid operations. Some researchers have proposed special purpose architectures that allow one to map some important problems directly onto the hardware and thus reduce the communication delay effects. But none of these studies have conclusively shown that the optimality observed on the sequential machines is conserved in time, and the number of processors needed, when these methods are implemented on multiprocessors, nor is there any clear understanding about the communication and the synchronization costs involved.

The work undertaken here is to explore the above mentioned questions further for shared and non-shared memory architectures. The effort is aimed at studying the effects of various implementations on the convergence rates. We are also studying the advantages and disadvantages of using a large number of simple processors versus a small number of powerful processors. The model problem considered here is that of solving 2-D incompressible Navier-Stokes equations in vorticity-stream function formulation. Experiments are being carried out on the commercially available MIMD machines such as the Intel Hyper-cube, Sequent, Encore, and the Flex/32. In addition to these studies, investigation is underway towards the development of new algorithms that possess some of the numerical properties of multigrid methods, but do not require tight synchronization.

David M. Nicol

A model problem, the Game of Life, has been implemented on an Intel Hypercube for the purpose of empirically studying dynamic load balancing policies. This code will serve as a testbed for (1) centralized, static "risk averting" policies, (2) dynamic scheduling of risk averting policies, (3) dynamic remapping of exact balance policies, (4) decentralized balancing policies. The simplicity of the model problem should allow a comparative study between these various methods. This work is being done with Joel Saltz.

We continue to develop analytic models which describe the behavior of dynamically evolving computations. We have recently been able to capture the phenomenon of correlation between pieces of work, derive the optimal static mapping of such workloads, and discuss optimal scheduling of dynamic remapping of these workloads. Further work will attempt to generalize this model. This work is also being done with Joel Saltz.

We are porting a subset of the ABL's CORBAN simulation to the FLEX/32. Once implemented this testbed will allow a study of the effectiveness of various load balancing policies, and will also allow a comparison of various synchronization protocols which have been proposed in the literature for distributed simulation. This work is being done with Joel Saltz, Paul Reynolds, and Frank Willard.

One problem which is often overlooked in parallel processing is the distribution of the number of processors to employ in solving a problem. Increasing the number of processors can improve parallelism while increasing overhead costs such as communication. We are attempting to analytically capture the relationships between execution and communication costs in order to determine an optimal allocation of processors to a given task, in a given architecture. This work is being done with Frank Willard.

We are attempting to explain the run-time behavior of backtracking search, using the N-Queens problem as a model. Two different methodologies have been developed for estimating the number of search tree nodes visited during a search; an optimally proof for the "most-constrained" dynamic search rearrangement strategy has also been constructed. Further work will validate and generalize these models. This work is being done with Harold Stone (International Business Machines).

Merrell L. Patrick

Computing systems of the future for large scale scientific and engineering computations will consist of many processors and memories working in parallel to solve a single problem. Efficient use and ease of use of these future systems are two basic problems facing potential users. The development of new parallel algorithms, parallel execution time models which predict the performance of the algorithms on different parallel architectures, and parallel programming environments for expressing the algorithms are essential for progress toward the solution of these problems.

Development of parallel algorithms and corresponding parallel execution time models for solving the generalized eigenvalue problem is continuing. Results from the models will be used to predict the performance of the algorithms on message passing and shared memory MIMD machines. The parallel algorithms will be integrated into a structural analysis system, NICE/SPAR, running on the FLEX/32 as a program module used in the dynamic analysis of a structure in motion. Several algorithms have been implemented and tested on the FLEX/32 at LaRC.

The algorithms developed will be used as a basis to continue work with T. Pratt and H. Jordan on defining the essential ingredients of parallel programming languages for scientific computations. Different programming paradigms will be used to program these algorithms on the FLEX/32 system.

Work with L. Adams and D. Reed determined optimal stencil/partition pairs for solving elliptic partial differential equations on MIMD machines. The optimality condition was to maximize the computation to communication ratio. Parallel execution time models were developed for message passing and shared memory architectures to predict the impact of the architecture on the choice of stencil/partition pairs. Results of the models are being validated on the FLEX/32. A paper based on this work has been accepted for publication in IEEE Transactions on Computers. Results from this work were extended by Voigt, Patrick, and Reed and were presented at "An International Conference on Vector and Parallel Computing," Loen, Norway, June 1986.

A study with J. Saltz and R. Voigt which attempts to answer the question as to whether SIMD architectures are sufficient for carrying out many of the computations arising in the solution of partial differential equations is

continuing. A thorough review of fundamental algorithms used in solving partial differential equations will be conducted in an attempt to identify those which require MIMD architectures.

Doug Peterson

The VAX computer was replaced in May, 1986, with a distributed system of Sun 3 computers, consisting of a model 3/180 file server and twelve model 3/50 diskless workstations connected via ethernet. All machines have a 32-bit architecture and 68020 cpu's. Each workstation is equipped with 4mb of RAM, two serial ports, and may be optionally equipped with a 71mb disk subsystem. Several workstations have ascii terminals connected to one of these serial ports, which provides second user login capability. The file server is equipped with 8mb of RAM, a 1600/6250bpi 9-track tape drive, two 380mb Fujitsu Eagle disk drives, two ethernet controllers, and 16 asynchronous serial ports. The file server also supports two laser printers, a dot matrix printer and several interactive terminal connections. A floating point accelerator module has been ordered, but has not yet been delivered. The second ethernet controller provides access to the NAS-Net, which in turn provides access to the ARPANET via a gateway at Ames Research Center. A MicroVax in the Computational Methods Branch, which is connected to the NAS-Net and LaRCNET, provides access to LaRCNET. Interactive access to ARPANET sites is unavailable from the Sun because the current release of the Sun operating system does not allow access to non-local hosts. It is expected that the next release, which will be available soon, will not have this restriction. In the interim, users requiring such access may establish accounts on other machines on the NAS-NET and bypass this restriction. This configuration has provided acceptable system performance, even during the summer, when demands on system resources increase due to visitors.

A domain-based electronic mail system has been established which provides service to the continental US, Canada, Great Britain, Europe, and the Middle East, and includes sites on CSNET, BITNET, and ARPANET. BITNET and CSNET sites are accessed through gateways which are ARPANET sites. UNIX sites in

the continental US not accessible through these networks can be reached through UUCP.

The IBM PC/AT's in the ICASE office will be networked with the Sun file server through ethernet using Sun Microsystems' NFS software. PC users will then have direct access to the file server disks, computing environment and communications capabilities, as well as the capability to run all current DOS applications on the PC.

The locally prepared document "Computing at ICASE" has been published and is currently undergoing revision to reflect recent changes in the ICASE computing environment. Except for graphics, this document was prepared on the Sun using available UNIX editors and document formatters. Although this document does not contain equations, editing still provided to be a tedious task because of the limitations of troff. The illustrations were done on the Macintosh.

An effort is currently in progress to upgrade the document publishing capabilities at ICASE. Systems being evaluated include WHYSIWYG systems, word processors, and text editors in conjunction with document formatters. The goal of this effort is to provide a complete document preparation and publishing system capable of integrating text, mathematical equations, and graphics from a wide range of input formats, including hand-written rough drafts and those prepared at other sites and transmitted to ICASE electronically. Additionally, the system should be able to support several ouput formats for electronic transmission to technical journals.

Terrence W. Pratt

The PISCES parallel programming environment allows the scientific programmer to write parallel programs that are intended to run on various parallel architectures. Programming is in PISCES Fortran (an extension of Fortran 77) under the Unix operating system. Several "granularities" of parallel operations are provided.

The PISCES 1 environment was implemented on the ICASE VAX 750 and on a network of Apollo Domain workstations at the University of Virginia. In

PISCES 1, a program is organized in clusters of tasks that communicate by passing messages.

The PISCES 2 environment is being designed and implemented for the FLEX/32 at LaRC. PISCES 2 extends PISCES 1 to include the 'force' constructs developed by H. Jordan which allow the programmer to make effective use of the shared memory of the FLEX/32. PISCES 2 also allows the programmer to control the mapping from PISCES clusters to the hardware processors.

The PISCES 2 implementation is nearing completion and will be made available to ICASE and NASA researchers.

Georg Propst

A widely employed approximation scheme for semigroups related to linear hereditary problems in the state space $\mathbb{R}^n \times L^2(-r,0;\mathbb{R}^n)$ uses splines for the function component coupling the vector component to the spline. In collaboration with K. Ito, it is shown that the corresponding adjoint semigroups do not converge strongly, which is essential for control problems.

Final adjustments are made on a scheme that uses discontinuous piecewise linear functions with a decoupled vector component. In this scheme, the adjoint semigroups and the feedback operators converge strongly even in the case of the infinite time horizon control problems.

Daniel A. Reed

Given a discretization stencil, partitioning the problem domain is an important first step for the efficient solution of partial differential equations on multiple processor systems. In collaboration with Loyce Adams and Merrell Patrick, we have derived partitions that minimize interprocessor communication when the number of processors is known a priori and each domain partition is assigned to a different processor. Our partitioning technique uses the stencil structure to select appropriate partition shapes. For square problem domains, we have shown that non-standard partitions (e.g., hexagons)

are frequently preferable to the standard square partitions for a variety of commonly used stencils. We have also formalized the relationship between partition shape, stencil structure, and architecture, allowing selection of optimal partitions for a variety of parallel systems.

We are currently investigating techniques for partitioning linear programming problems for parallel solution.

Joel H. Saltz and David M. Nicol

We consider the tradeoffs between the benefits and costs of balancing load in multiprocessor solutions of computational problems that describe the evolution of a physical system over the course of time. The type of architecture being assumed is one in which each processor has a local memory and the processors pass messages through either a communications network or a shared memory. The responsibility for computations pertaining to a given portion of problem domain is assigned to each processor. The data dependencies inherent in the solution of a time dependent problem cause the most heavily loaded processor to limit the rate at which the problem is solved. Frequently, the load in the portion of the problem assigned to each processor will vary, and without redistribution of load, system performance declines. While performance can be improved by a redistribution of load, this redistribution itself exacts a sometimes large delay cost.

Two probabilistic load models are proposed and used to evaluate policies for deciding when load balancing should be performed. Through use of these models, it is possible to characterize the relative performance of a number of different policies designed to determine when load should be balanced. This performance characterization is carried out through the derivation of analytic expressions and through simulation. Estimates of how the cost of balancing load interact with model parameters describing the number and activity of processors are obtained. Validation of these results is being carried out using an Intel iPSC hypercube implementation of Conway's game of life. This work is described in reports 86-45 and 86-46.

In a separate but related activity, a study is made of tradeoffs between communication costs and load imbalance in multiprocessors with preferential access to local memories, and between synchronization costs, and load imbalance in machines where the access time to all memory is approximately equal. Both analytic modelling and empirical studies on the Intel iPSC hypercube and the Encore multimax are carried out. The problem used in the empirical studies is that of solving sparse linear systems arising from finite difference discretizations of elliptic partial differential equations. The method used to solve these systems is a conjugate gradient type method orthomin preconditioned with incomplete LU factorizations. Wavefront methods are used to obtain parallelism in the forward and back solve of the sparse lower and upper triangular matrices required for preconditioning.

Parameterized mapping schemes are developed that allow one to adjust the granularity of parallelism in several different ways. The mapping chosen influences both the balance of load and the communication and synchronization overheads observed. The experimental results will be compared with analytic models of these tradeoffs in a particularly regular model problem as well as more general probabilistic models of these tradeoffs.

Joel H. Saltz and Hillel Tal-Ezer

The use of spectral methods in space to solve time dependent problems makes quite attractive the investigation of efficient high accuracy schemes to march the solution forward in time quite attractive. Richardson extrapolation of leapfrog and Crank Nicholson time integration methods for the solution of these partial differential equations can produce efficient high order schemes and can be used in a number of different ways to facilitate efficient solutions of spectral problems on a variety of multiprocessor architectures. Our investigation takes into account both numerical convergence as well as algorithm performance on message passing and shared memory multiprocessors.

A detailed analysis is carried out of a model hyperbolic problem solved by the pseudospectral Fourier method in space and extrapolated Leap-Frog scheme in time. Estimates of parallel efficiency are calculated from the analysis of

several ways of mapping the model problem onto a range of message passing and shared memory architectures. Given a desired error tolerance for time integration, taking into account the multiprocessor machine architecture, and the number of mesh points used to solve the model problem, we have developed a model that predicts the optimal number of extrapolations that should be carried out. Experimental results on the convergence and stability of the extrapolated algorithms have been encouraging, and an experimental analysis of the performance of these algorithms on the Flex/32 multiprocessor is being carried out.

Paul Saylor, Joel H. Saltz, and David M. Nicol

A reduction in the asymptotic computational complexity of a number of common iterative methods appears, in some cases, to be achievable through a simple modification of the algorithms. Statistical estimation techniques are exploited in order to reduce the computation required in the calculation of the inner products required in the conjugate gradient method and of iteration matrix eigenvalues required for implementation of optimal Chebyshev acceleration. The size of the sample required for the statistical estimation and, consequently, the computation required to form the statistical estimate vary with the precision required of the estimate. Methods of determining sample size given a priori and observed measures of the problem behavior are being investigated. The utility of sampling in the estimation of inner products and iteration matrix eigenvalues is significant in the solution of very large scale problems involving millions of variables. Experimental work to elucidate the usefulness of these methods on vector and multiprocessor architectures is being carried out.

Ke-Gang Shih and Shlomo Ta'asan

A multigrid continuation method is applied to the bifurcation problem of Bénard convection in a rectangular box. A plan is also made to study the

imperfect bifurcation of this problem when there are imperfect insulation side walls.

Charles G. Speziale

Subgrid scale stress and heat flux models have been developed in collaboration with M. Y. Hussaini, T. Zang (High-Speed Aerodynamics Division, LaRC), and G. Erlebacher (High-Speed Aerodynamics Division, LaRC) for the large-eddy simulation of compressible turbulent flows. These models have been shown to correlate favorably with direct numerical simulations of homogenous, compressible turbulence and satisfy all of the necessary invariance requirements. A large-eddy simulation of homogeneous, compressible turbulence is currently being considered, and future applications to aerodynamic problems involving the generation of shock waves are envisioned.

The development of second-order closure models suitable for the analysis of incompressible turbulent flows with in-plane curvature has been investigated in collaboration with T. B. Gatski (High-Speed Aerodynamics Division, LaRC). By making an analogy with rotating turbulent flows, a modification in existing second-order closures has been developed which appears to be more suitable for the analysis of such curved turbulent flows. The goal of this study is to use this model to gain a better understanding of the reduced turbulence intensities and shear stresses that occur in problems involving in-plane curvature. This could have useful applications to the field of aerodynamic drag reduction.

Eitan Tadmor

Work on entropy conservative finite element methods is continued. The work on our nonoscillatory central differencing code is being summarized. We study convenient TVD conditions for highly accurate schemes for such scalar laws.

Together with D. Gottlieb, we continue with research on spectral recovery of discontinuous data, including the problem of jumps locators. The work on implementation of such a recovery for propagation of singularities in linear hyperbolic problems is being summarized.

Hillel Tal-Ezer

Previously (ICASE reports 84-8, 85-9), we have described an algorithm designed to solve numerically time-dependent problems. This algorithm results in a scheme which has spectral accuracy both in time and space. It can be implemented for problems where the domain of eigenvalues of the spatial operator has a specific orientation: either close to the imaginary axis or close to the negative real axis. In many geophysical problems, the domain of eigenvalues is a union of the two previous cases. In our present research, we try to implement the approach described in 84-8 and 85-9 for these kinds of problems. The algorithm is based on approximating the function ρ^z as a finite sum of Faber polynomials.

In previous ICASE reports (83-66, 86-1) it was shown that a straightforward implementation of Chebyshev pseudospectral methods for the numerical solution of a system of hyperbolic equations results in an unstable scheme. In the present research, we look into this phenomenon. One way to construct a stable scheme for these problems is based on characteristic variables analysis and modifying the boundary conditions accordingly. Another way to treat this phenomenon is based on the pseudospectral-Tau-Legendre method. It can be shown that for the nondissipative hyperbolic system, the scheme which results is stable. The advantage of this approach is in the fact that it does not depend on any knowledge of characteristic variables.

The problem of designing an iterative method for the numerical solution of a system $AX = b$ where A is a nonsymmetric matrix is treated. Since $x = A^{-1}b$, we look into it as a problem of approximating the function $\frac{1}{z}$ in a domain in the complex plane. It is known that a polynomial approximation based on expanding $\frac{1}{z}$ as a sum of Faber polynomials is "almost best." An algorithm based on this approach is designed.

Sherryl Tomboulian

Methods for using SIMD architectures to solve large graph-type problems, such as circuit simulation and semantic networks, are explored. A simple SIMD architecture model that is bit-serial and uses only nearest neighbor connections is proposed. Each vertex in the graph is uniquely assigned to a processor in the machine model. The connections between processors are realized using a marking scheme which instructs the processors to pass messages to their immediate neighbors in such a way as to guarantee that no two message connections conflict. All connections can be traversed, in parallel, in time O(diameter of network x ac), where ac is the average number of connections per vertex in the graph. A new connection can be added or modified in the same time.

Eli Turkel

A project was completed on the properties of global approximation methods. We consider the ability of such methods to resolve functions with sharp gradients or with discontinuities in some derivative. In particular, it was found that the method resolved gradients better near the boundary than in the center. This occurred for several sequences of collocation nodes. Similar phenomena were investigated for both hyperbolic and elliptic partial differential equations. In general, it was found that global methods behave very differently than local methods even though similar collocation nodes are used. An ICASE report together with A. Solomonoff has been completed.

Work also continued on the use of Runge-Kutta marching algorithms to solve the steady state Euler and Navier-Stokes equations. Work has concentrated on the robustness of such techniques both with regard to convergence rates and with respect to the accuracy of the converged solution. It was found that the solution is very sensitive to the artificial viscosity. Small changes in the artificial viscosity can change the lift and drag by 5-10% on intermediate grids, e.g., a 160x32 C mesh. Even on finer grids the accuracy is very sensitive to changes in the artificial viscosity. Also large oscillations in the total pressure were found near the trailing edge when a C mesh was used.

Such oscillations did not appear when using an O mesh. The sensitivity of the parameters of the residual smoothing was also investigated. Improvements in the multigrid code were made so that now the residual is reduced by one order of magnitude for each ten iterations of the five-state Runge-Kutta algorithm on the fine mesh.

Bram van Leer

There is increasing evidence that the combination of the multigrid strategy with explicit, non-sequential (non-sweeping) relaxation algorithms is potentially the most efficient way of numerically solving the Navier-Stokes or Euler equations on a vector-computer. While the multigrid framework is now sufficiently understood and established through testing, explicit relaxation methods so far have been constructed by trial and error on the basis of multi-stage Runge-Kutta schemes.

It can be shown that all design criteria for a multigrid-purpose relaxation method (efficient damping of short waves in all directions) can be met by a sequence of two-level (predictor-corrector) schemes with a block coefficient (rather than a scalar) multiplying the residual. The research will include the full analysis of the short-wave filter and its application to a baseline of test problems.

Jeff Yost and John Van Rosendale

As parallel architectures become available, fluid dynamics problems which can currently be solved only with great difficulty and expense will become routine. In collaboration with Gordon Erlebacher (High-Speed Aerodynamics Division, LaRC), we are studying parallel numerical methods for three-dimensional free-boundary problems. We are looking at several distinct approaches, tetrahedronal Langrangian mesh methods, SLIC methods, and the Hasselgar and Wolfram cellular automata models.

We are also studying approaches to visualizing the computed flows. One approach is based on a recently developed program which interpolates arbitrary point sets using triangular splines and then forms images by ray-tracing. Another approach avoids explicit constructions of the interpolating surface but, instead, uses an implicit surface defined through what are called "blobby molecules." The first approach has the advantage that it allows surface tension calculations and fits well with tetrahedronal mesh programs. The second approach is better suited to cellular automata models but may not be able to produce high quality images.

REPORTS AND ABSTRACTS

Mac Giolla Mhuiris, Nessan: *The construction and use of divergence free vector expansions for incompressible fluid flow calculations.* ICASE Report No. 86-20, April 15, 1986, 21 pages. Submitted to Proceedings of a Spectral Methods Workshop.

For incompressible fluids the law of mass conservation reduces to a constraint on the velocity vector, namely that it be divergence free. This constraint has long been a source of great difficulty to the numericist seeking to discretize the Navier-Stokes and Euler equations. In this paper we will discuss a spectral method which overcomes this difficulty and we will demonstrate its efficacy on some simple problems. The velocity is approximated by a finite sum of divergence free vectors, each of which satisfies the same boundary conditions as the velocity. Projecting the governing equations onto the space of inviscid vector fields eliminates the pressure term and produces a set of ordinary differential equations that must be solved for the coefficients in the velocity sum. The pressure can then be recovered if it is needed.

Bayliss, A., K. E. Jordan, B. J. LeMesurier, and E. Turkel: *A fourth order accurate finite difference scheme for the computation of elastic waves.* ICASE Report No. 86-21, April 23, 1986, 44 pages. Submitted to Bulletin of the Seismological Society of America.

A finite difference for elastic waves is introduced. The model is based on the first order system of equations for the velocities and stresses. The differencing is fourth order accurate on the spatial derivatives and second order accurate in time. The model is tested on a series of examples including the Lamb problem, scattering from a plane interface and scattering from a fluid-elastic interface. The scheme is shown to be effective for these problems. The accuracy and stability are insensitive to the Poisson ratio. For the class of problems considered here we find that the fourth order scheme requires from two-thirds to one-half the resolution of a typical second order scheme to give comparable accuracy.

Harten, Ami, Bjorn Engquist, Stanley Osher, and Sukumar R. Chakravarthy: *Uniformly high order accurate essentially non-oscillatory schemes III.* ICASE Report No. 86-22, April 29, 1986, 97 pages. Submitted to J. Comput. Phys.

In this paper, a third in a series we continue the construction and the analysis of essentially non-oscillatory shock capturing methods for the

approximation of hyperbolic conservation laws. We present a hierarchy of uniformly high order accurate schemes which generalizes Godunov's scheme and its second order accurate MUSCL extension to arbitrary order of accuracy. The design involves an essentially non-oscillatory piecewise polynomial reconstruction of the solution from its cell averages, time evolution through an approximate solution of the resulting initial value problem, and averaging of this approximate solution over each cell. The reconstruction algorithm is derived from a new interpolation technique that when applied to piecewise smooth data gives high-order accuracy whenever the function is smooth but avoids a Gibbs phenomenon at discontinuities. Unlike standard finite difference methods this procedure uses an adaptive stencil of grid points and consequently the resulting schemes are highly nonlinear.

Ta'asan, Shlomo: *Multigrid method for the equilibrium equations of elasticity using a compact scheme.* ICASE Report No. 86-23, April 30, 1986, 25 pages. Submitted to J. of Comp. Physics.

A compact difference scheme derived in [3] for treating the equilibrium equations of elasticity is studied. The scheme turns out to be inconsistent and unstable. A multigrid method which takes into account these properties is described. The solution of the discrete equations, up to the level of discretization errors, is obtained by this method in just two multigrid cycles.

Reed, Daniel A., Loyce M. Adams, and Merrell L. Patrick: *Stencils and problem partitionings: their influence on the performance of multiple processor systems.* ICASE Report No. 86-24, May 2, 1986, 47 pages. Submitted to IEEE Trans. Comput.

Given a discretization stencil, partitioning the problem domain is an important first step for the efficient solution of partial differential equations on multiple processor systems. We derive partitions that minimize interprocessor communication when the number of processors is known a priori and each domain partition is assigned to a different processor. Our partitioning technique uses the stencil structure to select appropriate partition shapes. For square problem domains, we show that non-standard partitions (e.g., hexagons) are frequently preferable to the standard square partitions for a variety of commonly used stencils. We conclude with a formalization of the relationship between partition shape, stencil structure, and architecture, allowing selection of optimal partitions for a variety of parallel systems.

Hussaini, M. Y. and T. A. Zang: *Spectral methods in fluid dynamics.* ICASE Report No. 86-25, May 5, 1986, 61 pages. Submitted to Annual Review of Fluid Mechanics.

Fundamental aspects of spectral methods are introduced. Recent developments in spectral methods are reviewed with an emphasis on collocation techniques. Their applications to both compressible and incompressible flows, to viscous as well as inviscid flows, and also to chemically reacting flows are surveyed. The key role that these methods play in the simulation of stability, transition, and turbulence is brought out. A perspective is provided on some of the obstacles that prohibit a wider use of these methods and how these obstacles are being overcome.

Hussaini, M. Y., W. D. Lakin, and A. Nachman: *On similarity of a boundary layer problem with an upstream moving wall.* ICASE Report No. 86-26, May 9, 1986, 25 pages. Submitted to SIAM J. Appl. Math.

This work deals with the problem of a boundary layer on a flat plate which has a constant velocity opposite in direction to that of the uniform mainstream. It has previously been shown that the solution of this boundary value problem is crucially dependent on the parameter which is the ratio of the velocity of the plate to the velocity of the free stream. In particular, it was proved that a solution exists only if this parameter does not exceed a certain critical value, and numerical evidence was adduced to show that this solution is nonunique. Using Crocco formulation the present work proves this nonuniqueness. Also considered are the analyticity of solutions and the derivation of upper bounds on the critical value of wall velocity parameter.

Chen, T. F. and G. J. Fix: *Least squares finite element simulation of transonic flows.* ICASE Report No. 86-27, May 9, 1986, 28 pages. Submitted to Applied Numerical Mathematics.

Finite difference approximation of transonic flow problems is a well-developed and largely successful approach. Nevertheless, there is still a real need to develop finite element methods for applications arising from fluid-structure interactions and problems with complicated boundaries. In this paper we introduce a least squares based finite element scheme. It is shown that, if suitably formulated, such an approach can lead to physically meaningful results. Bottlenecks that arise from such schemes are also discussed.

Kopriva, David: *A spectral multidomain method for the solution of hyperbolic systems*. ICASE Report No. 86-28, May 9, 1986, 47 pages. Submitted to Applied Numerical Mathematics.

A multidomain Chebyshev spectral collocation method for solving hyperbolic partial differential equations has been developed. Though spectral methods are global methods, an attractive idea is to break a computational domain into several subdomains, and a way to handle the interfaces is described. The multidomain approach offers advantages over the use of a single Chebyshev grid. It allows complex geometries to be covered, and local refinement can be used to resolve important features. For steady-state problems it reduces the stiffness associated with the use of explicit time integration as a relaxation scheme. Furthermore, the proposed method remains spectrally accurate. Results showing performance of the method on one-dimensional linear models and one- and two-dimensional nonlinear gas-dynamics problems are presented.

Ta'asan, Shlomo: *Multigrid method for a vortex breakdown simulation*. ICASE Report No. 86-29, May 9, 1986, 22 pages. Submitted to Applied Numerical Mathematics.

In this paper, we study an inviscid model for a steady axisymmetric flow with swirl. The governing equation is a nonlinear elliptic equation which has more than one solution for a certain range of the swirl parameter. The physically interesting solutions have closed streamlines that look like vortex breakdown ("bubble"-like solutions). A multigrid method is used to find these solutions. Using an FMG algorithm (nested iteration), the problem is solved in just a few multigrid cycles.

Gunzburger, M. D. and R. A. Nicolaides: *On structuring algorithms and solution techniques for the numerical approximation of partial differential equations*. ICASE Report No. 86-30, May 9, 1986, 32 pages. Submitted to Applied Numerical Mathematics.

Substructuring methods are in common use in mechanics problems where typically the associated linear systems of algebraic equations are positive definite. Here these methods ae extended to problems which lead to non-positive definite, nonsymmetric matrices. The extension is based on an algorithm which carries out the block Gauss elimination procedure without the need for interchanges even when a pivot matrix is singular. Examples are provided wherein the method is used in connection with finite element solutions of the stationary Stokes equations and the Helmholtz equation, and dual methods for second-order elliptic equations.

Strikwerda, J. C., B. A. Wade, and K. P. Bube: *Regularity estimates up to the boundary for elliptic systems of difference equations.* ICASE Report No. 86-31, May 8, 1986, 65 pages. Submitted to SIAM J. Numer. Anal.

We prove regularity estimates up to the boundary for solutions of elliptic systems of finite difference equations. The regularity estimates, obtained for boundary-fitted coordinate systems on domains with smooth boundary, involve discrete Sobolev norms and are proved using pseudo-difference operators to treat systems with variable coefficients. The elliptic systems of difference equations and the boundary conditions which are considered are very general in form. We prove that regularity of a regular elliptic system of difference equations is equivalent to the nonexistence of "eigensolutions." The regularity estimates obtained are analogous to those in the theory of elliptic systems of partial differential equations and to the results of Gustafsson, Kreiss, Sundstrom [1972], and others for hyperbolic difference equations.

Burns, J. A., E. M. Cliff, and R. K. Powers: *Computational methods for the control of distributed parameter systems.* ICASE Report No. 86-32, May 12, 1986, 18 pages. Submitted to Proc. of the 24th IEEE Conf. on Decesion and Control.

Finite dimensional approximation schemes that work well for distributed parameter systems are often not suitable for the analysis and implementation of feedback control systems. The relationship between approximation schemes for distributed parameter systems and their application to optimal control problems is discussed. A numerical example is given.

Tadmor, Eitan: *A minimum entropy principle in the gas dynamics equations.* ICASE Report No. 86-33, May 20, 1986, 20 pages. Submitted to Applied Numerical Mathematics.

Let $u(\overline{x},t)$ be a weak solution of the Euler equations, governing the inviscid polytropic gas dynamics; in addition, $u(\overline{x},t)$ is assumed to respect the usual entropy conditions connected with the conservative Euler equations. We show that such entropy solutions of the gas dynamics equations satisfy a minimum entropy principle, namely, that the spatial minimum of their specific entropy, $\operatorname{Ess}\inf_{\overline{x}} S(u(\overline{x},t))$ is an increasing function of time. This principle equally applies to discrete approximations of the Euler equations such as the Godunov-type and Lax-Friedrichs schemes. Our derivation of this minimum principle makes use of the fact that there is a family of generalized entropy functions connected with the conservative Euler equations.

Mac Giolla Mhuiris, Nessan: *Calculations of the stability of some axisymmetric flows proposed as a model of vortex breakdown.* ICASE Report No. 86-34, May 20, 1986, 36 pages. Submitted to Applied Numerical Mathematics.

The term "vortex breakdown" refers to the abrupt and drastic changes of structure that can sometimes occur in swirling flows. It has been conjectured that the "bubble" type of breakdown can be viewed as an axisymmetric wave travelling upstream in a primarily columnar vortex flow. In this scenario the wave's upstream progress is impeded only when it reaches a critical amplitude and it loses stability to some axisymmetric wavy flows, which model vortex breakdown, to three dimensional disturbances viewing the amplitude of the wave as a bifurcation parameter. We will also look at the stability of a set of related, columnar vortex flows which are constructed by taking the two dimensional flow at a single axial location and extending it throughout the domain without variation. The method of our investigation will be to expand the perturbation velocity in a series of divergence free vectors which ensures that the continuity equation for the incompressible fluid is satisfied exactly by the computed velocity field. Projections of the stability equation onto the space of inviscid vector fields eliminates the pressure term from the equation and reduces the differential eigen problem to a generalized matrix eigen problem. Results are presented both for the one dimensional, columnar vortex flows, and also for the wavy "bubble" flows.

Speziale, Charles G.: *On the advantages of the vorticity-velocity formulation of the equations of fluid dynamics.* ICASE Report No. 86-35, May 20, 1986, 10 pages. Submitted to Applied Numerical Mathematics.

The mathematical properties of the pressure-velocity and vorticity-velocity formulations of the equations of viscous flow are compared. It is shown that a vorticity-velocity formulation exists which has the interesting property that non-inertial effects only enter into the problem through the implementation of initial and boundary conditions. This valuable characteristic, along with other advantages of the vorticity-velocity approach, are discussed in detail.

South, Jerry C., Jr., Mohammed M. Hafez, and David Gottlieb: *Stability analysis of intermediate boundary conditions in approximate factorization schemes.* ICASE Report No. 86-36, May 20, 1986, 27 pages. Submitted to Applied Numerical Mathematics.

The paper discusses the role of the intermediate boundary condition in the AF2 scheme used by Holst for simulation of the transonic full potential equation. We show that the treatment suggested by Holst led to a restric-

tion on the time step and suggest ways to overcome this restriction. The discussion is based on the theory developed by Gustafsson, Kreiss, and Sundstrom and also on the von Neumann method.

Swanson, R. C. and E. Turkel: *Pseudo-time algorithms for the Navier-Stokes equations*. ICASE Report No. 86-37, May 21, 1986, 32 pages. Submitted to Applied Numerical Mathematics.

A pseudo-time method is introduced to integrate the compressible Navier-Stokes equations to a steady state. This method is a generalization of a method used by Crocco and also by Allen and Cheng. We show that for a simple heat equation that this is just a renormalization of the time. For a convection-diffusion equation the renormalization is dependent only on the viscous terms. We implement the method for the Navier-Stokes equations using a Runge-Kutta type algorithm. This enables the time step to be chosen based on the inviscid model only. We also discuss the use of residual smoothing when viscous terms are present.

Banks, H. T. and D. W. Iles: *On compactness of admissible parameter sets: convergence and stability in inverse problems for distributed parameter systems*. ICASE Report No. 86-38, June 9, 1986, 16 pages. Submitted to Proc. IFIP Conf. on Control Systems Governed by Partial Differential Equations.

We report on a series of numerical examples and compare several algorithms for estimation of coefficients in differential equation models. Unconstrained, constrained and Tikhonov regularization methods are tested for their behavior with regard to both convergence (of approximation methods for the states and parameters) and stability (continuity of the estimates with respect to perturbations in the data or observed states).

Erlebacher, Gordon and Yousuff Hussaini: *Incipient transition phenomena in compressible flows over a flat plate*. ICASE Report No. 86-39, June 10, 1986, 21 pages. Submitted to Proc. 10th Inter. Conf. on Num. Methods in Fluid Dynamics.

The full three-dimensional time-dependent compressible Navier-Stokes equations are solved by a Fourier-Chebychev method to study the stability of compressible flows over a flat plate. After the code is validated in the linear regime, it is applied to study the existence of the secondary instability mechanism in the supersonic regime.

Iqbal, M. Ashraf: *Approximate algorithms for partitioning and assignment problems*. ICASE Report No. 86-40, June 10, 1986, 16 pages. Submitted to IEEE Trans. Computers.

We consider the problem of optimally assigning the modules of a parallel/pipelined program over the processors of a multiple computer system under certain restrictions on the interconnection structure of the program as well as the multiple computer system. We show that for a variety of such programs it is possible to find in linear time if a partition of the program exists in which the load on any processor is within a certain bound. This method, when combined with a binary search over a finite range, provides an approximate solution to the partitioning problem.

The specific problems we consider are partitioning of (1) a chain structured parallel program over a chain-like computer system, (2) multiple chain-like programs over a host-satellite system and (3) a tree structured parallel program over a host-satellite system.

For a problem with m modules and n processors, the complexity of our algorithm is no worse than $O(mn\log(W_T/\varepsilon))$, where W_T is the cost of assigning all modules to one processor and ε the desired accuracy.

Bokhari, Shahid: *Multiprocessing the sieve of Eratosthenes*. ICASE Report No. 86-41, June 17, 1986, 26 pages. Submitted to IEEE Computer.

The well known Sieve of Eratosthenes for finding prime numbers dates back to about 200 B.C. In recent years it has seen much use as a benchmark algorithm for serial computers while its intrinsically parallel nature has gone largely unnoticed.

We describe the implementation of a parallel version of this algorithm for a real parallel computer, the Flex/32, and discuss its performance. It is shown that the algorithm is sensitive to several fundamental performance parameters of parallel machines, such as spawning time, signaling time, memory access, and overhead of process switching. Because of the nature of the algorithm, it is impossible to get any speedup beyond 4 or 5 processors unless some form of dynamic load balancing is employed. We describe the performance of our algorithm with and without load balancing and compare it with theoretical lower bounds and simulated results.

It is straightforward to understand this algorithm and to check the final results. However its efficient implementation on a real parallel machine requires thoughtful design, especially if dynamic load balancing is desired. The fundamental operations required by the algorithm are very simple: this means that the slightest overhead appears prominently in performance data. The Sieve thus serves not only as a very severe test of the capabilities of a parallel processor but is also an interesting challenge for the programmer.

Nicolaides, R. A.: *Construction of higher order accurate vortex and particle methods*. ICASE Report No. 86-42, June 13, 1986, 20 pages. Submitted to Applied Numerical Mathematics.

The standard point vortex method has recently been shown to be of high order of accuracy for problems on the whole plane, when using a uniform initial subdivision for assigning the vorticity to the points. If obstacles are present in the flow, this high order deteriorates to first or second-order. This paper introduces new vortex methods which are of arbitrary accuracy (under regularity assumptions) regardless of the presence of bodies and the uniformity of the initial subdivision.

Lamm, Patricia K. and Katherine A. Murphy: *Estimation of discontinuous coefficients and boundary parameters for hyperbolic systems*. ICASE Report No. 86-43, June 18, 1986, 39 pages. Submitted to Quarterly of Applied Math.

We consider the problem of estimating discontinuous coefficients, including locations of discontinuities, that occur in second order hyperbolic systems typical of those arising in 1-D surface seismic problems. In addition, we treat the problem of identifying unknown parameters that appear in boundary conditions for the system. A spline-based approximation theory is presented, together with related convergence findings and representative numerical examples.

Goldberg, Moshe and Eitan Tadmor: *Convenient stability criteria for difference approximations of hyperbolic initial-boundary value problems II*. ICASE Report No. 86-44, June 25, 1986, 38 pages. Submitted to Mathematics of Computation.

The purpose of this paper is to extend the results of [4] in order to achieve more versatile, convenient stability criteria for a wide class of finite-difference approximations to initial boundary value problems associated with the hyperbolic system $u_t = Au_x + Bu + f$ in the quarter-plane $x \geq 0$, $t \geq 0$. With these criteria, stability is easily established for a large number of examples, thus incorporating and generalizing many of the cases studied in recent literature.

Nicol, David M. and Joel H. Saltz: *Dynamic remapping of parallel computations with varying resource demands*. ICASE Report No. 86-45, July 18, 1986, 55 pages. Submitted to IEEE Transactions on Computers.

A large class of computational problems are characterized by frequent synchronization and computational requirements which change as a function of time. When such a problem must be solved on a message passing multiprocessor machine, the combination of these chracteristics leads to system performance which decreases in time. Performance can be improved with periodic redistribution of computational load; however, redistribution can exact a sometimes large delay cost. We study the issue of deciding when to invoke a global load remapping mechanism. Such a decision policy must effectively weigh the costs of remapping against the performance benefits. We treat this problem by constructing two analytic models which exhibit stochastically decreasing performance. One model is quite tractable; we are able to describe the optimal remapping algorithm, and the optimal decision policy governing when to invoke that algorithm. However, computational complexity prohibits the use of the optimal remapping decision policy. We then study the performance of a general remapping policy on both analytic models. This policy attempts to minimize a statistic $W(n)$ which measures the system degradation (including the cost of remapping) per computation step over a period of n steps. We show that as a function of time, the expected value of $W(n)$ has at most one minimum, and that when this minimum exists it defines the optimal fixed-interval remapping policy. Our decision policy appeals to this result by remapping when it estimates that $W(n)$ is minimized. Our performance data suggest that this policy effectively finds the natural frequency of remapping. We also use the analytic models to express the relationship between performance and remapping cost, number of processors, and the computation's stochastic activity.

Saltz, Joel H. and David M. Nicol: *Statistical methodologies for the control of dynamic remapping*. ICASE Report No. 86-46, July 8, 1986, 33 pages. Submitted to Proceeding ARO.

Following an intial mapping of a problem onto a multiprocessor machine or computer network, system performance often deteriorates with time. In order to maintain high performance, it may be necessary to remap the problem. The decision to remap must take into account measurements of performance deterioration, the cost of remapping, and the estimated benefits achieved by remapping. We examine the tradeoff between the costs and the benefits of remapping two qualitatively different kinds of problems. One problem assumes that performance deteriorates gradually; the other assumes that performance deteriorates suddenly. We consider a variety of policies for governing when to remap. In order to evaluate these policies, statistical models of problem behaviors are developed. Simulation results are presented which compare simple policies with computationally expensive optimal decision policies; these results demonstrate that for each problem type, the proposed simple policies are effective and robust.

Poore, Aubrey B.: *The expanded Langrangian system for constrained optimization problems.* ICASE Report No. 86-47, July 9, 1986, 29 pages. Submitted to SIAM Journal on Control and Optimization.

Smooth penalty functions can be combined with numerical continuation/bifurcation techniques to produce a class of robust and fast algorithms for constrained optimization problems. The key to the development of these algorithms is the Expanded Lagrangian System which is derived and analyzed in this work. This parameterized system of nonlinear equations contains the penalty path as a solution, provides a smooth homotopy into the first-order necessary conditions, and yields a global optimization technique. Furthermore, the inevitable ill conditioning present in a sequential optimization algorithm is removed for three penalty methods: the quadratic penalty function for equality constraints, and the logarithmic barrier function (an interior method) and the quadratic loss function (an exterior method) for inequality constraints. Although these techniques apply to optimization in general and to linear and nonlinear programming, calculus of variations, optimal control and parameter identification in particular, the development is primarily within the context of nonlinear programming.

Maestrello, Lucio, Alvin Bayliss, Paresh Parikh, and Eli Turkel: *Stability and control of compressible flows over a surface with concave-convex curvature.* ICASE Report No. 86-48, July 9, 1986, 34 pages. Submitted to Journal of Fluid Mechanics.

The active control of spatially unstable disturbances in a laminar, two-dimensional, compressible boundary layer over a curved surface is numerically simulated. The control is effected by localized time-periodic surface heating. We consider two similar surfaces of different heights with concave-convex curvature. In one, the height is sufficiently large so that the favorable pressure gradient is sufficient to stabilize a particular disturbance. In the other case the pressure gradient induced by the curvature is destabilizing. It is shown that by using active control that the disturbance can be stabilized. The results demonstrate that the curvature induced mean pressure gradient significantly enhances the receptivity of the flow to localized time-periodic surface heating and that this is a potentially viable mechanism in air.

Rosenfeld, M., M. Israeli, and M. Wolfshtein: A *numerical study of separation on a spheroid at incidence.* ICASE Report No. 86-49, July 11, 1986, 35 pages. Submitted to AIAA.

The three-dimensional incompressible, steady and laminar flow field around a prolate spheroid at incidence is considered. The parabolized

Navier-Stokes equations are solved numerically. The method can handle vortex type as well as bubble type flow separation because the pressure is one of the dependent variables. In the present paper the distribution of the skin friction is reported for two test cases. The first test case is a prolate spheroid of aspect ratio of 4:1 at 6^{o} incidence and Reynolds number of 10^{6} (based on half the major axis). The second case is a spheroid with a 6:1 aspect ratio at 10^{o} incidence and Reynolds number of 0.8×10^{6}. The properties of the flow field near the body are discussed on the basis of the pattern of the skin friction lines, and the shape of the separation lines. Favorable agreement with experimental results is obtained.

Sidi, Avram and Moshe Israeli: *Numerical quadrature methods for integrals of singular periodic functions and their application to singular and weakly singular integral equations*. ICASE Report No. 86-50, July 16, 1986, 35 pages. Submitted to J. of Num. Anal.

High accuracy numerical quadrature methods for integrals of singular periodic functions are proposed. These methods are based on the appropriate Euler-Maclaurin expansions of trapezoidal rule approximations and their extrapolations. They are used to obtain accurate quadrature methods for the solution of singular and weakly singular Fredholm integral equations. Such periodic equations are used in the solution of planar elliptic boundary value problems, elasticity, potential theory, conformal mapping, boundary element methods, free surface flows, etc. The use of the quadrature methods is demonstrated with numerical examples.

Lustman, Liviu R. and Milton E. Rose: *A three dimensional calculation of elastic equilibrium for composite materials*. ICASE Report No. 86-51, July 24, 1986, 28 pages. Submitted to Int. Journal for Numerical Method in Engineering.

A compact scheme is applied to three-dimensional elasticity problems for composite materials, involving simple geometries. The mathematical aspects of this approach are discussed, in particular the iteration method. A vector processor code implementing the compact scheme is presented, and several numerical experiments are summarized.

Hariharan, S. I. and S. I. Sudharsanan: *Wave envelope technique for multimode wave guide problems*. ICASE Report No. 86-52, July 30, 1986, 29 pages. Submitted to Applied Numerical Mathematics.

In this paper we propose a fast method for solving wave guide problems. In particular, we consider the guide to be inhomogeneous as well as allowing propagation of waves of higher-order modes. Such techniques have been handled successfully for acoustic wave propagation problems with single mode and finite length. This paper extends this concept to electromagnetic wave guides with several modes and infinite in length. The method is shown and results of computations are presented.

Nicol, David M.: *Optimal partitioning of random programs across two processors*. ICASE Report No. 86-53, August 1, 1986, 26 pages. Submitted to IEEE Trans. on Software Engineering.

Recent work by Indurkya et al. discusses the optimal partitioning of random distributed programs. They conclude that the optimal partitioning of a homogeneous random program over a homogeneous distributed system either assigns all modules to a single processor, or distributes the modules as evenly as possible among all processors. Their analysis rests heavily on the approximation which equates the expected maximum of a set of independent random variables with the set's maximum expectation. In this paper we strengthen Indurkya's results by providing an approximation-free proof of this result for two processors under general conditions on the module execution time distribution. We also show that use of this approximation causes two of Indurkya's central results to be false.

Jordan, Harry F.: *The force on the Flex: Global parallelism and portability*. ICASE Report No. 86-54, August 5, 1986, 21 pages. Submitted to the Parallel Processing and Medium Scale Multiprocessors Proceedings of the Army Research Workshop at Stanford University, January 6 - 8, 1986, SIAM Press.

A parallel programming methodology, called the force, supports the construction of programs to be executed in parallel by an unspecified, but potentially large, number of processes. The methodology was originally developed on a pipelined, shared memory multiprocessor, the Denelcor HEP, and embodies the primitive operations of the force in a set of macros which expand into multiprocessor Fortran code. A small set of primitives is sufficient to write large parallel programs, and the system has been used to produce 10,000 line programs in computational fluid dynamics. The level of complexity of the force primitives is intermediate. It is high enough to mask detailed architectural differences between multiprocessors but low enough to give the user control over performance.

The system is being ported to a medium scale multiprocessor, the Flex/32, which is a 20 processor system with a mixture of shared and local memory. Memory organization and the type of processor synchronization

supported by the hardware on the two machines lead to some differences in efficient implementations of the force primitives, but the user interface remains the same. An initial implementation was done by retargeting the macros to Flexible Computer Corporation's ConCurrent C language. Subsequently, the macros were caused to directly produce the system calls which form the basis for ConCurrent C. The implementation of the Fortran based system is in step with Flexible Computer Corporation's implementation of a Fortran system in the parallel environment.

Nicol, David M.: *Expected performance of m-solution backtracking.* ICASE Report No. 86-55, August 5, 1986, 25 pages. Submitted to SIAM Journal of Computing.

This paper derives upper bounds on the expected number of search tree nodes visited during an m-solution backtracking search, a search which terminates after some preselected number m problem solutions are found. The search behavior is assumed to have a general probabilistic structure. Our results are stated in terms of node expansion and contraction. A visited search tree node is said to be expanding if the mean number of its children visited by the search exceeds 1 and is contracting otherwise. We show that if every node expands, or if every node contracts, then the number of search tree nodes visited by a search has an upper bound which is linear in the depth of the tree, in the mean number of children a node has, and in the number of solutions sought. We also derive bounds linear in the depth of the tree in some situations where an upper portion of the tree contracts (expands), while the lower portion expands (contracts). While previous analyses of 1-solution backtracking have concluded that the expected performance is always linear in the tree depth, our model allows super-linear expected performance. By generalizing previous work in the expected behavior of backtracking, we are better able to identify classes of trees which can be searched in linear expected time.

Jackson, T. L.: *Effect of thermal expansion on the stability of two-reactant flames.* ICASE Report No. 86-56, August 18, 1986, 13 pages. Submitted to Combined Science and Technology.

The full problem of flame stability for the two-reactant model, which takes into account thermal expansion effects for all disturbance wave lengths, is examined. It is found that the stability problem for the class of two-reactant flames is equivalent to the stability problem for the class of one-reactant flames with an appropriate interpretation of Lewis numbers.

Hussaini, M. Y.: *Recent developments in spectral methods*. ICASE Report No. 86-57, August 29, 1986, 19 pages. Submitted to Proc. 10th Inter. Conf. Num. Meth. in Fluid Dynamics.

This paper is solely devoted to spectral iterative methods including spectral multigrid methods. These techniques are explained with reference to simple model problems. Some Navier-Stokes algorithms based on these techniques are mentioned. Results on transition simulation using these algorithms are presented.

Nicol, David M. and Paul F. Reynolds: *Dynamic remapping decisions in multiphase parallel computations*. ICASE Report No. 86-58, September 8, 1986, 47 pages. Submitted to IEEE Trans. on Computers.

The effectiveness of any given mapping of workload to processors in a parallel system is dependent on the stochastic behavior of the workload. Program behavior is often characterized by a sequence of phases, with phase changes occurring unpredictably. During a phase, the behavior is fairly stable, but may become quite different during the next phase. Thus a workload assignment generated for one phase may hinder performance during the next phase. We consider the problem of deciding whether to remap a parallel computation in the face of uncertainty in remapping's utility. Fundamentally, it is necessary to balance the expected remapping performance gain against the delay cost of remapping. This paper treats this problem formally by constructing a probabilistic model of a computation with at most two phases. We use stochastic dynamic programming to show that the remapping decision policy which minimizes the expected running time of the computation has an extremely simple structure: the optimal decision at any step is followed by comparing the probability of remapping gain against a threshold. This theoretical result stresses the importance of detecting a phase change and assessing the possibility of gain from remapping. We also empirically study the sensitivity of optimal performance to imprecise decision thresholds. Under a wide range of model parameter values, we find nearly optimal performance if remapping is chosen simply when the gain probability is high. These results strongly suggest that except in extreme cases, the remapping decision problem is essentially that of dynamically determining whether gain can be achieved by remapping after a phase change; precise quantification of the decision model parameters is not necessary.

Street, C. L. and M. Y. Hussaini: *Finite length effects in Taylor-Couette flow*. ICASE Report No. 86-59, September 9, 1986, 30 pages. Submitted to Proc. Workshop on "The Stability of Time-Dependent/Spatially Varying Flows."

Axisymmetric numerical solutions of the unsteady Navier-Stokes equations for flow between concentric rotating cylinders of finite length are obtained by a spectral collocation method. These representative results pertain to two-cell/one-cell exchange process and are compared with recent experiments.

Solomonoff, A. and E. Turkel: *Global collocation methods for approximation and the solution of partial differential equations.* ICASE Report No. 86-60, September 17, 1986, 67 pages. Submitted to Journal of Computational Physics.

We apply polynomial interpolation methods both to the approximation of functions and to the numerical solutions of hyperbolic and elliptic partial differential equations. We construct the derivative matrix for a general sequence of the collocation points. The approximate derivative is then found by a matrix times vector multiply. We explore the effects of several factors on the performance of these methods including the effect of different collocation points. We also study the resolution of the schemes for both smooth functions and functions with steep gradients or discontinuities in some derivative. We investigate the accuracy when the gradients occur both near the center of the region and in the vicinity of the boundary. The importance of the aliasing limit on the resolution of the approximation is investigated in detail. We also examine the effect of boundary treatment on the stability and accuracy of the scheme.

Bernardi, Canuto, Maday: *Generalized inf-sup condition for Chebyshev approximation of the Navier-Stokes equations.* ICASE Report No. 86-61, November 7, 1986, 67 pages. Submitted to SIAM J. Num. Analysis.

We study an abstract mixed problem and its approximation; both are well-posed if and only if several inf-sup conditions are satisfied. These results are applied to a spectral Galerkin method for the Stokes problem in a square, when it is formulated in Chebyshev weighted Sobolev spaces. Finally, a collocation method for the Navier-Stokes equations at Chebyshev nodes is analyzed.

Gunzburger, M.D.: *Mathematical aspects of finite element methods for incompressible viscous flows.* ICASE Report No. 86-62, September 18, 1986, 46 pages. Submitted to Springer-Verlag.

We survey some mathematical aspects of finite element methods for incompressible viscous flows, concentrating on the steady primitive

variable formulation. We address the discretization of a weak formulation of the Navier-Stokes equations; we then consider the div-stability condition, whose satisfication insures the stability of the approximation. Specific choices of finite element spaces for the velocity and pressure are then discussed. Finally, the connection between different weak formulations and a variety of boundary conditions is explored.

LeVeque, Randall J. and Lloyd N. Trefethen: *Fourier analysis of the SOR iteration*. ICASE Report No. 86-63, September 30, 1986, 9 pages. Submitted to SIAM J. Num. Anal.

The SOR iteration for solving linear systems of equations depends upon an overrelaxation factor ω. We show that for the standard model problem of Poisson's equation on a rectangle, the optimal ω and corresponding convergence rate can be rigorously obtained by Fourier analysis. The trick is to tilt the space-time grid so that the SOR stencil becomes symmetrical. The tilted grid also gives insight into the relation between convergence rates of several variants.

April	1	**Professor O. Pironneau**, INRIA, France: *Numerical Simulation of Compressible Viscous Flow Around Airplanes*
April	8	**Mr. C. C. H. Ma**, University of Waterloo: *Direct Adaptive Regulation and Tracking - A Stable Coprime Factorization Approach*
April	10	**Professor Richard B. Pelz**, Princeton University: *On the Role of Helicity in Turbulent Flows*
April	23	**Mr. Ching-Yi Wang**, Rensselaer Polytechnic Institute: *Access Control in a Heterogeneous Distributed Database Management System*
April	28	**Mr. Sanjay Rajopadhye**, University of Utah: *Synthesizing Systolic Arrays from Recurrence Equations*
May	1	**Dr. Pieter Buning**, NASA Ames Research Center: *Graphic and Flow Visualization in Computational Fluid Dynamics*
May	5	**Ms. Lenore Zuck**, The Weizmann Institute of Science, Israel: *Verification of Multiprocess Probabilistic Protocols*
May	12	**Dr. Jon A. Sjogren**, Duke University: *Tree-Splitting Iteration for Markov Analysis*
May	15	**Mr. Chuck Romine**, University of Virginia: *Analysis of Parallel Factorization Methods*
May	21	**Mr. Lee Higbie**, Sullivan Computer Corporation: *The CHoPP Computer*
May	27	**Mr. David R. O'Hallaron**, University of Virginia: *Petri Net Liveness Results*
May	29	**Professor Paul Saylor**, University of Illinois: *Reorganizing Standard Iterative Methods to Improve Efficiency*

June 2 **Professor Antony Jameson**, Princeton University: *Inviscid Transonic Flow Over A Complete Airplane*

June 2 **Professor Antony Jameson**, Princeton University: *Multigrid and TVD Schemes*

June 3 **Professor Shmuel Kaniel**, The Hebrew University of Jerusalem, Israel: *Transport Approach to the Isentropic Compressible Flow Equations*

June 4 **Professor Shmuel Kaniel**, The Hebrew University of Jerusalem, Israel: *Numerical Solution of the Isentropic Compressible Flow Equations via the Transport Approach*

June 18 **Professor George Vahala**, The College of William and Mary: *Decimation in Turbulence*

July 10 **Dr. Robert Krasny**, Courant Institute of Mathematical Sciences: *Computation of Vortex Sheet Roll-Up in the Trefftz Plane*

July 11 **Professor Moshe Israeli**, Princeton University: *On Pressure Boundary Conditions in Incompressible Hydrodynamics*

July 15 **Professor Ali Nayfeh**, Virginia Polytechnic Institute and State University: *Effect of Roughness on the Stability of Boundary Layers*

July 22 **Dr. Philip Roe**, Cranfield Institute of Technology, United Kingdom: *Accuracy of Cell-Vertex Solutions to Conservation Laws*

July 25 **Professor Harry Dwyer**, University of California, Davis: *Combustion Modelling with or Without Adaptive Grid*

August 1 **Dr. Philip Hall**, Exeter University, England: *The Interaction of Large Amplitude Tollmien-Schlichting Waves and Cortler Vortices*

August 4 **Mr. P. D. Manhardt**, Computational Mechanics Corporation, Knoxville, TN and **Professor A. J. Baker**, University of Tennessee: *Array Processing of the Three-Dimensional Navier-Stokes Equations*

August 11 **Mr. Dennis M. Bushnell**, NASA Langley Research Center: *Aeronautics Beyond the Year 2000*

August 13 **Ms. Sherry Tomboulian**, Duke University: *An Algorithm for Connected Information Processing on SIMD Architectures*

August 14 **Professor Jack Dennis**, Dataflow Technology Corporation and Massachusetts Institute of Technology: *Dataflow Computation: A Case Study*

September 11 **Dr. Eli Turkel**, Tel-Aviv University: *Multigrid and Runge-Kutta Methods for Transonic Flows*

September 24 **Dr. John Cantrell**, NASA Langley Research Center: *Acoustic Radiation Stress and the Thermodynamic Properties of Solids*

ICASE SUMMER ACTIVITIES

The summer program for 1986 included the following visitors:

NAME/AFFILIATION	DATE OF VISIT	AREA OF INTEREST
Abarbanel, Saul Tel-Aviv University	8/ 4 - 10/31	Computational Fluid Dynamics
Adams, Loyce University of Washington	7/28 - 8/15	Numerical Methods for Parallel Computing Systems
Baines, Michael J. University of Reading England	7/28 - 8/2	AdaptiveFinite Element Methods for Hyperbolic Equations
Banks, H. Thomas Brown University	6/ 9 - 6/20	Control Theory
Bayliss, Alvin Exxon Corporate Research	8/18 - 8/29	Numerical Methods for Fluid Flow and Acoustics
Brandt, Achi The Weizmann Institute of Science, Israel	7/21 - 7/25	Multigrid Methods
Brewer, Dennis University of Arkansas	6/16 - 7/11	Control Theory
Burns, John A. Virginia Polytechnic Institute	6/ 9 - 6/20	Control Theory
Canuto, Claudio Palazzo dell´ University Italy	8/18 - 8/29	Spectral Methods for PDE´s
Cowley, Stephen Imperial College of Science and Technology England	9/ 1 - 9/26	Computational Fluid Dynamics
Crowley, James M. U. S. Air Force Academy	9/ 1 - 9/26	Control Theory
Fix, George Carnegie-Mellon University	6/30 - 8/1	Numerical Methods for PDE´s

NAME/AFFILIATION	DATE OF VISIT	AREA OF INTEREST
Gannon, Dennis Indiana University	5/ 5 - 5/7	Parallel Processing Systems
Gibson, J. Steven University of California, LA	6/16 - 6/26	Control Theory
Glowinski, Roland University of Houston	10/20 - 10/31	Numerical Methods for PDE's
Gokhale, Maya University of Delaware	6/23 - 7/4	Parallel Computing Systems
Gottlieb, David Brown University	5/19 - 8/29	Numerical Methods for PDE's
Gunzburger, Max Carnegie-Mellon University	5/26 - 5/30 8/11 - 8/15	Numerical Methods for PDE's
Hall, Philip Exeter University, England	6/30 - 9/26	Computational Fluid Dynamics
Hariharan, Subramaniya I. University of Akron	5/19 - 6/27	Computational Acoustics
Harten, Amiram University of California, LA	6/30 - 9/12	Numerical Methods for PDE's
Hirsch, Richard S. John Hopkins University	7/ 7 - 7/18	Numerical Methods for PDE's
Inman, Daniel J. State University of New York Buffalo	6/16 - 6/20	Numerical Methods for Inverse Problems in Distributed Systems
Israeli, Moshe Princeton University	6/ 2 - 8/29	Computational Fluid Dynamics
Ito, Kazufumi Brown University	6/09 - 6/27	Control Theory
Jacobs, Marc Air Force Office of Scientific Research	6/ 9 - 6/13	Control Theory
Jordan, Harry F. University of Colorado	6/ 9 - 6/20 8/ 4 - 8/8	Parallel Processing Systems

NAME/AFFILIATION	DATE OF VISIT	AREA OF INTEREST
Kaniel, Shmuel The Hebrew University of Jerusalem, Israel	6/ 2 - 6/6	Numerical Solution of Compressible Flow Equations
Kapila, Ashwani Rensselaer Polytechnic Institute	6/ 2 - 6/6	Mathematical Aspects of Combustion Processes
Keeling, Stephen L. University of Tennessee	6/ 9 - 6/13	Analysis of Methods for the Solution of Parabolic PDE's
Keyes, David Yale University	5/27 - 7/18	Parallel Methods Appropriate for Combustion Problems
Kojima, Fumio Kyoto Institute of Technology Japan	6/16 - 6/27	Control Theory
Kopriva, David Florida State University	7/21 - 8/1	Spectral Methods for Problems in Fluid Dynamics
Krasny, Robert Courant Institute	6/30 - 7/11	Vortex Sheet Evolution
Lamm, Patricia D. Southern Methodist University	6/ 9 - 6/13	Control Theory
LeVegue, Randall University of Washington	7/28 - 8/6	Numerical Methods for PDE's
Maday, Yvon Universite Pierre et Marie Curie, France	9/ 1 - 9/19	Analysis of Spectral Methods PDE's
Majda, George Ohio State University	8/11 - 8/15	Numerical Methods for PDE's
Mavriplis, Dimitri Princeton University	6/ 2 - 6/27	Grid Techniques for Computational Fluid Dynamics
Mehrotra, Piyush Purdue University	6/30 - 7/4	Programming Languages for Multiprocessor Systems

NAME/AFFILIATION	DATE OF VISIT	AREA OF INTEREST
Milman, Mark California Institute of Technology	6 /9 - 6/13	Control Theory
Murphy, Katherine A. Brown University	6/ 9 - 6/20	Control Theory
Napolitano, Michele Universita Di Bari, Italy	7/20 - 9/26	Computational Fluid Dynamics
Nicolaides, R. A. Carnegie-Mellon University	5/19 - 5/23 8/11 - 8/15	PDE's Using Finite Element Techniques
Obayashi, Shigeru University of Tokyo Japan	7/ 7 - 8/29	Computational Fluid Dynamics
Osher, Stanley J. University of California, LA	7/ 7 - 7/18	Numerical Techniques for Problems in Fluid Dynamics
Patrick, Merrell L. Duke University	5/12 - 6/20 8/18 - 8/29	Algorithms for Parallel Array Computers
Poore, Aubrey Colorado State University	6/ 9 - 6/13	Numerical Methods for Optimal Control
Pratt, Terrence W. University of Virginia	6/ 2 - 6/6	Programming Languages
Reed, Daniel A. University of Illinois	6/ 2 - 6/13	Performance of Parallel and Distributed Systems
Reyna, Luis T. J. Watson Research Center	8/11 - 8/15	Numerical Methods for PDE's
Roe, Philip L. Royal Aircraft Establishment England	7/14 - 8/8	Computational Fluid Dynamics
Rosen, I. Gary University of Southern CA	6/ 9 - 6/20	Numerical Methods for Problems in Control Systems
Sakawa, Yoshiyuki Osaka University Japan	6/16 - 6/27	Control Theory

NAME/AFFILIATION	DATE OF VISIT	AREA OF INTEREST
Saylor, Paul University of Illinois	5/19 - 5/30	Iterative Parallel Methods for Linear Systems
Shapiro, Richard S. Massachusetts Institute of Technology	6/30 - 8/29	Computational Fluid Dynamics
Smith, Frank T. University College London, England	9/ 1 - 9/26	Theory and Computation of Boundary Layer Instabilities and Transition
Sundararajan, N. Indian Space Research Organization, India	8/ 4 - 8/29	Adaptive Control of Large Space Structures
Tadmor, Eitan Tel-Aviv University Israel	6/23 - 8/29	Numerical Method for PDE's
Tal-Ezer, Hillel Tel-Aviv University Israel	7/21 - 10/10	Numerical Methods for PDE's
Temam, Roger Universite de Paris-Sud France	9/19 - 9/25	Numerical Methods for PDE's
Trefethen, L. N. Massachusetts Institute of Technology	7/14 - 7/18	Numerical Methods for PDE's
Turkel, Eli Tel-Aviv University Israel	6/23 - 9/26	Computational Fluid Dynamics
van Leer, Bram Delft University of Technology, Netherlands	7/21 - 8/1	Computational Fluid Dynamics
Van Rosendale, John University of Utah	5/ 5 - 5/ 9 6/23 - 7/4	Parallel Processing Systems
Vavasis, Stephen Stanford University	6/23 - 9/19	Computational Complexity of Parallel Algorithms

NAME/AFFILIATION	DATE OF VISIT	AREA OF INTEREST
White, Robert North Carolina State University	6/ 9 - 6/20	Control Theory and Parallel Algorithms
Yost, Jeffery University of Utah	6/23 - 9/12	Computer Graphics for Computational Fluid Dynamics

OTHER ACTIVITIES

A workshop on Finite Element Theory and Application hosted by ICASE/NASA was held July 28-30, 1986, at the Sheraton Inn Coliseum in Hampton, Virginia. The purpose of this workshop was to bring leading mathematicians working in finite element theory together with leading practitioners in the areas of structural analysis, heat transfer, and fluid dynamics. Fourteen researchers were invited to speak, and their papers will be collected into a volume published by Springer. The speakers and their topics are listed below:

S. N. Atluri Georgia Institute of Technology: *Computational Mechanics and Control of Finite Deformations of Inelastic Solids*

I. Babuska University of Maryland: *H-P Finite Element Methods*

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16. Abstract

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